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REVIEW ARTICLE

Hydrological impacts of afforestation - A review of research in India

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Abstract: We review the current status of experimental studies in India to understand the linkages between afforestation and hydrology. This discipline deals with the use and management of water, social awareness of environmental problems, and ecosystem limitations on provision of watershed services by river basins in the mountain regions of India. Our review begins with examination of experimental works in tropical countries and proceeds to discussion of initiatives of Indian research institutes and Government organizations towards establishing experimental watersheds to understand the impacts of land cover changes on hydrologic regimes in the Indian sub-continent. This is followed by the review of the experimental work carried out by various authors to assess the impact of land cover changes on major water balance components such as, runoff, groundwater, evapotranspiration and sediment yield. The spatial scales of these experiments have been limited to small watersheds or field plots. This paper also describes impacts of human interventions (such as plantations of exotic forest species to restore degraded landscapes) on the water balance components in diverse hydro-geo-environmental conditions in the Indian sub-continent. We focus on identifying the research areas which require immediate attention to develop tools to assist planners and policy makers in assessing and managing the water resources in these complex environments. The review is largely based on research results reported during the last 20 to 30 years.

Key Words: afforestation, Western Ghats, experimental watersheds, land-use/cover changes, humid tropics

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Introduction

Tropical forests are known to perform several hydrological functions including flood attenuation, sustaining dry season flows and maintaining rainfall patterns. However, due to the increasing population and associated developmental activities, forest areas in developing countries such as India are being replaced by alternative land uses. Hydrological impacts of forest degradation in tropical regions are well documented (e.g., Meher-Homji 1991). However, it must be noted that in an effort to offset loss of forests, degraded and open lands are being brought under extensive plantations of fast growing monocultures, often of exotic tree species. In contrast to impacts of deforestation, the effects of such afforestation activities on the hydrological regime are less well understood. Not surprisingly, concerns are being raised that increased establishment of plantations of exotic forest species either through conversion of native forests and scrublands or afforestation of pasture and native grassland may have detrimental effects on the environment and on the disposition of water balance components of the area.

Assessment of these impacts requires intensive and detailed field investigations, but due to constraints imposed by time and costs, such studies can be taken up only in field plots or in small watersheds. Only at small spatial scales is it possible to establish experimental networks necessary for continuous long-term observations involving interdisciplinary efforts of hydrologists with other natural scientists. Realizing the importance of sustainable land and water resources management, many such field experiments have been conducted to quantify the impacts of vegetation changes on the water balance of catchments.

Considerable progress has been made in process hydrology research only in the temperate latitudes. In comparison, the humid tropics have received less attention, mostly for social and economic reasons (Bonell 1991). Bonell (2005) provides a detailed review of process hydrology studies carried out in the humid tropics. Owing to the limited number of studies undertaken in the humid tropics, it is not surprising to note the transfer of technology from the humid temperate regions, even though environmental conditions are different and thus the applicability some-

what tenuous. An even greater constraint is the small number and limited scope of inquiry into hydrological process work to assist in the interpretation of water balance studies (Bonell et al. 1981).

In India, research in forest hydrology received attention as early as the 1960s, when the Central Soil & Water Conservation Research & Training Institute, Research Centre (CSWCRTI), established experimental watersheds near Dehra Dun. But inadequate progress has been made since then. However, the late 1980s saw a renewed interest in forest hydrology following reports in the media that *Eucalyptus* sp. (or eucalypt) plantations lead to mining of groundwater sources (Calder et al. 1992; Vandana & Bhandopadyaya 1983). Since then, forest hydrology studies emphasizing the impacts of afforestation on hydrological regimes have been pursued. This paper provides a review of Indian experimental studies carried out to understand the effects of afforestation on various water balance components.

Effect of reforestation on runoff and sediment yield

Runoff yield from afforested watersheds

Mathur et al. (1976) studied paired catchments to assess the impact of forest clear felling and reforestation on hydrologic regimes at Dehra Dun, Uttaranchal state. Two watersheds possessing the same climatic, soil and geologic characteristics but with different land-uses, viz., a watershed with brush forest, and one with *Eucalyptus* species, were studied. The experiments were carried out for a period of nine years. The watershed with eucalypts yielded 23% less runoff than the forested watershed. Also, the peak runoff rate was reduced by 73%. A similar study revealed that thinning (20 percent of original stand) yielded a significant (8.6%) increase in peak flow during the first year, but subsided in subsequent years due to changes in vegetation cover (Subba Rao et al. 1985). However, reduction in total flow volume was found to be non-significant. More recently, watershed-scale studies on hydrological behavior of Himalayan watersheds have been carried out under managed land use conditions. Seventeen micro watersheds with contrasting land uses and topographic conditions were monitored for stream flows (the areas of the watersheds ranged from 52 to 240 ha and included forest, scrub agriculture and mixed oak forest). The study reported that the subsurface flow contribution to the annual discharge was higher than that of the surface flow (Anon. 2005). Further, forested watersheds sustained lean season flows in comparison to the other watersheds that did not.

Numerous studies were carried out in the Shiwalik hills at the foot of the Himalayas and showed that runoff ranged from 17 to 48% of rainfall, depending upon the size and land cover conditions of the watershed. A long term analysis of rainfall, runoff and peak discharge in a 21.3 ha watershed in Punjab, indicated a decline in average annual water yield of 22.06% in 1964–65 to 6.92% over a span of 20 years with no significant change in peak discharge (Anon. 2003). Vijay Kumar et al. (2007) studied the event-based response from a small forested watershed near Jammu, India. They found that the runoff coefficient was as high as 0.92 for a 36-mm rainfall event and as low as 0.03 for 19 mm of rainfall (Fig.1). Their highest observed rainfall event of 210 mm yielded a runoff coefficient of 0.86. This phenomenon clearly indicates that when the catchment is receiving continuous rainfall, i.e., when the catchment is saturated, even a fully forested catchment can produce runoff as high as a degraded watershed. A similar observation was reported by Scott et al. (2005) in other parts of the humid tropics.

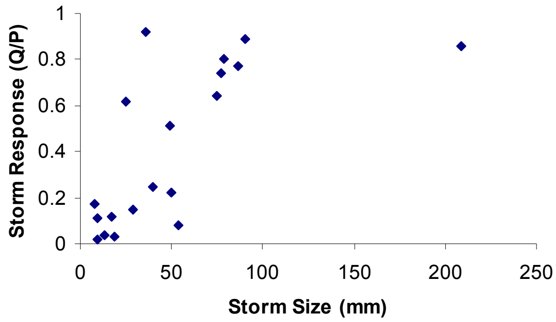

Fig. 1. Storm response from a forested small watershed in Shiwalik (Vijayakumar et al. 2007)

Jain et al. (2000) investigated linkages between hydrology and ecology through a study of Khecheopalri Lake and its surrounding watershed (12 km^2) in Sikkim. Their objective was to assess the long-term impact of landuse change on the hydrology of the lake ecosystem. Overland flow increased while baseflows decreased, the latter being most important to sustenance of the lake ecosystem. However, in a similar study, Satapathy and Datta (2007) reported that afforestation increased baseflow by 20–40% over pre-afforestation levels in the upland hills of northeast India.

The Western Ghats (more popularly known as Sahayadri Mountains), the source of most of the major rivers in peninsular India, has seen widespread plantation of eucalypts on barren and cleared areas as part of a government sponsored afforesation strategy. However, this strategy has met with stiff opposition from environmental groups and Non-Governmental Organizations (NGOs), since it is believed that eucalypts are voracious consumers of water (Vandana and Bandhopadhyay 1983). In an attempt to evaluate the negative effects of eucalypt plantations, CSWCRTI, Dehradun established experimental watersheds in the Nilgiri hills of the Western Ghats. Samraj et al. (1988) and Sharda et al. (1988) analyzed hydrological data collected from these watersheds over a 10 year rotation period. Results indicated that the conversion of natural grasslands into eucalypt plantations reduced water yield by 16% during the first 10 years with a reduction in total flow averaging 87 mm per year. Sikka et al. (1998) analyzed long term data gathered from two similar watersheds, one with natural grassland and the other planted with eucalypts, to evaluate the hydrological implications of converting natural grassland to bluegum (a species of *Eucalyptus*) plantation in the Nilgiris. They observed a greater reduction in seasonal runoff volume from the bluegum-planted watershed during winter and summer. The treated watershed was clear-felled at 10-

year intervals. Runoff declined by 25.4% during the second clear-felling as compared to a 16% reduction in water yield during the first clear-felling. Sharda (1998) studied the implications of coppiced bluegum growth from 1982-1991, and found that mean annual flow declined by 25.4% and baseflow by 27% in comparison with the first 10 year period. The reduction in runoff peaked during July to October and was ascribed to greater availability and utilization of rainwater. The increased utilization of water during the second rotation was attributed to the deep root system of bluegum. Sikka et al. (2003) analyzed long term data of these watersheds to understand the effects of converting grasslands to eucalypt plantation on low flows and peak flows. They used the Low Flow Index (LFI), defined as the 10-day average flow which is exceeded 95% of the time, to represent the effect of plantation forest cover on the low-flow regime. Reductions in LFI by 2.0 and 3.75 times for the bluegum-planted watershed over the grassland during the first and second rotations, respectively, clearly indicated the effect of bluegum on the stream flow regime.

James et al. (2000) studied the impact of forest degradation by selecting three watersheds representing different intensities of forest degradation (dense forest, partially exploited, fully exploited). The forested watersheds stored more water and had higher flow duration compared to the exploited watersheds. However, Unni (Personal Communication) reported high variation in the baseflow index under different land-uses such as tea, coffee, cardamom, eucalypt, cashew and rubber (58% for rubber and 96% for tea).

Numerous studies have in the humid tropics have evaluated the impacts of changes in land use/cover on runoff generation mechanisms and soil hydraulic properties (e.g., Bonell et al. 1983, Elsenbeer et al. 1992, Elsenbeer and Vertessy 2000, Zimmermann et al. 2006). However, few Indian studies have addressed these issues. A notable exception is the field survey carried out by Putty and Prasad (2000a, b) in the headwater catchments of river Cauvery in the Western Ghats to understand runoff generation mechanisms. They reported the existence of a dynamic subsurface saturated zone flow (SSF) mechanism within a pipe network consisting of macropores, and saturation overland flow in addition to return flow below the pipe outlets. Also, they observed very high surface infiltration rates (150–900 mm/h) and percolation rates below 0.5 m in the range 100–300 mm/h. These authors suggest that deep SSF was the dominant stormflow pathway, especially through pipes whose outlets in stream banks had diameters varying from a few mm to more than 1 metre. Putty (2006) reported on contrasting storm hydrographs that emerged from forest versus grassland catchments. The former produced steep rising limbs but relatively shallow-graded recessions, which reflected the role of pipe flow in draining the catchment more slowly. In contrast, the grassland showed a more “flashy” storm hydrograph response with steep rising limbs and steep recessions, which Putty (2006) attributed to infiltration-excess overland flow as a dominant pathway.

However, no studies have assessed the impacts of changes in land use/cover on soil hydraulic properties, especially field saturated hydraulic conductivity K_{sat}. These properties and rainfall intensities at short time intervals are most important from the viewpoint of identifying preferential flow paths and runoff generation mechanisms. While this issue has been studied in some detail across the humid tropics and higher latitudes (Bonell 2005; Elsenbeer and Vertessy 2000), Negi (2002) reported that no such studies were undertaken in the Himalayan region. Some preliminary investigations to characterize the soils in the Western Ghats have been made by Venkatesh et al. (2004) and Purandara et al. (2001). These studies involved measurements of soil hydraulic properties in a small watershed in Uttara Kannada District, Karnataka State. The watershed was covered entirely by teak and mixed forest on black cotton soils. Measured values of saturated hydraulic conductivity were 4.6 mm/h for mixed forest and 2.3 mm/h for teak forest.

Sediment yield from the afforested watersheds

Samraj et al. (1977) studied patterns of soil loss under various types of vegetative cover, such as shola forest (forest associated with a mountain stream), bluegum plantation, black wattle (common name for a number of species of Acacia), and indigenous grass. These experiments were conducted on plots of 20 m × 10 m in Ootacamund (Nilgiri Mountains) in Tamilnadu during 1968–1971. The study revealed that there was no soil loss from shola forest and indigenous grass plots, whereas the bluegum and black wattle plots yielded slightly more soil loss in comparison to shola forest and grass plots. Sastry and Dhruva Narayana (1984) monitored two forested watersheds of 4.4 (W2C) ha and 70.4 (W3B) ha comprised of sal (*Shorea robusta*) trees of 60–80 years age growing at a density of about 400 trees per ha in Doon valley. The watershed W3B was protected against any disturbance whereas W2C was grazed by cattle. Brushwood check dams were constructed in W2C in 1976 to study the soil and water losses from the watershed. The average annual runoff (1972–1975) from watershed W2C before treatment was 223 mm which declined to 195 mm (average of 1976–1983) after the treatment. W2C had a relatively high sediment production rate before treatment (4.7 t/ha) and declined by 54% (2.8 t/ha) after treatment. Soil loss in the ungrazed W3B was lower (1.6 t/ha) than in the untreated or treated W2C. Jain et al. (2000) investigated the impact of land cover change from 1963 to 1997 on the hydrology of the lake ecosystem in Sikkim of northeast India. The major land cover changes reported were the expansion of bog area, farmland and settlements. Soil loss was highest in converted farmland followed by bare land, forest and cardamom agroforestry. Sahoo et al. (2007) reported negligible (0.97 t/ha) soil loss in a well maintained grassland in comparison to that of the untreated watersheds located in the Nilgiris, Tamilnadu. Krishnaswamy et al. (2006) studied the impact of open-cast iron ore mining activities on sediment loading in the river Bhadra flowing through Kudremukh National Park in Karnataka State. They monitored the sediment load by sampling water at two locations on river Bhadra, one before the river entered the mining area and other downstream of the mine. The sediment load in the river at the downstream location increased from 53% in 1985 to 67% in 1986. The study concluded that mining was the single

largest source of sediment (>50%) in the basin although the mining was confined to less than 0.22% of the basin. Similarly, Kumar and James (2007) reported greater sediment loss from a fully exploited watershed on the order of 4.8 to 5.5 times that from fully forested watersheds located in the parts of the Western Ghats in Kerala.

Effect of reforestation on groundwater

Mathur and Raj (1980) monitored subsurface water level fluctuations in a watershed supporting bluegum plantation located in the Nilgiris of Tamilnadu. A network of five piezometers was installed to measure the water level fluctuations during 1979–1980. Initial observations indicated that the maximum water level fluctuation was 1.3 m. The existing water level was well below the root zone of bluegum trees at certain locations but was within the root zone in topographic lows. The study did not find higher water utilization by the trees even when the water table was within the active root zone. While investigating groundwater recharge magnitudes in field plots under different land cover types, Purandara et al. (1998) reported negligible groundwater level fluctuation in a 20 year old eucalypt plantation. Groundwater recharge was highest in the forested watershed followed by teak plantation, eucalypt plantation, and degraded land. The study also involved monitoring of soil moisture content (SMC) in these plots to a depth of 2 m for a period of one year. Although a declining trend in SMC with depth was recorded, significant differences between land cover types could not be inferred because the roots of forest and plantation trees extended below the 2 m depth. Therefore, the authors were unable to relate changes in SMC to groundwater fluctuations.

Estimating evapotranspiration under reforestation

Calder et al. (1992) measured transpiration from individual *Eucalyptus tereticornis* trees in plantations at Devabal, Hoskote, Puradal, and Dandupalya of Karnataka State using deuterium tracing. The transpiration of trees was measured during the non-water stress period (in the month of February) for 4 years (1987-1990). The highest transpiration rate was recorded at Dandupalya (7.35 mm·day^{-1}) and the lowest transpiration rate was at Puradal (0.24 mm·day^{-1}). The rate of transpiration for *Eucalyptus camaldulensis* was 6 mm·day^{-1} at Puradal site in Karnataka (Roberts and Rosier 1993).

In a similar study, Kallarackal and Somen (1997a) investigated transpiration rates in a 4-year-old *Eucalyptus grandis* plantation in Kerala state. Measurements carried out during 1992 involved monitoring of weather parameters above the canopy and also transpiration measurements at individual leaves. The lowest transpiration of 2.49 mm·day^{-1} was recorded in March 1992 and the highest of 6.94 mm·day^{-1} in May 1992. In another study, Kallarackal and Somen (1997b) selected two plantations of *Eucalyptus tereticornis*, one in central Kerala and the other 250 distant in the southern part of the state. Measured hourly transpiration rates at these sites varied between 0.4 to 1.2 mm·h^{-1} and 0.2 to 0.6 mm·h^{-1}, yielding daily totals of about 3.5 to 7.7 mm·day^{-1} and 2.0 to 4.9 mm·day^{-1}, respectively. Kallarackal and Somen (2004) reported evapotranspiration estimates under different land-uses, viz, *Eucalyptus tereticornis*, *Eucalyptus grandis*, *Acaica auriculiformis*, *Acaica occidentale*, *Aevea braziliensis* and *Tectona grandis*. Annual transpiration from *E. grandis* was highest at 1679 mm (128% of the annual rainfall of 1302 mm). Lowest annual transpiration was 59% of annual rainfall of 3350 mm (1926 mm) for *H. braziliensis*. Annual transpiration estimates for *A. auriculiformis* and *A. occidentale* were 63% of annual rainfall of 3176 mm (2053 mm) and 84% of annual rainfall of 2461 mm (2059 mm).

The important role played by interception on the overall water balance and in particular transpiration processes of forested areas is widely recognized. Bruijnzeel (1990) noted that in natural forests, interception may constitute 4.5% to 24% of the incident rainfall depending on its intensity. Measurements made in an oak forest in the Garhwal hills, Uttaranchal state, indicated interception values varying from 11% of daily rainfall of <10 mm to 7.4% for daily rainfall of >100 mm (Sharda & Ojasvi, personal communication). In contrast, Kumar and James (2007) reported interception rates of 92% for daily rainfall of 2.5 mm and 4.5% for daily rainfall of 135 mm in the Western Ghats.

Discussion

This review of hydrological studies of the hydrological impacts of afforestation in the Himalayas and Western Ghats has helped in recognizing the areas where some knowledge has been accumulated and in identifying the major knowledge gaps. Initiatives of different researchers can provide a useful foundation for developing appropriate strategies/scopes for future research.

Looking at the hydrological studies conducted under different land use/cover, rainfall regimes, soil types and geological conditions, it is difficult to apply the results of one study to another location. Most of the studies are carried out on a very small watershed scale with a unique land use. Bruijnzeel and Bremmer (1989) concluded that any change in vegetation type or land use does not exert any clear influence on the total water and sediment yield in the smaller catchments. But in larger watersheds >1000 km^2, not only the land-use, but other parameters such as climate, topography and geology also play a major role in controlling water and sediment yields (Wilk 2000). Given this situation, only the spatial hydrological models can be used to identify and assess those areas vulnerable to land degradation, and provide information to inform afforesation planning.

The impact of afforestation cannot be assessed only in hydrological terms: it needs to be explored with reference to other related fields such as soils, ecology and sociology. Hence, it requires an inter-disciplinary approach. But we found no studies from India to evaluate the socio-economic impacts of land cover changes.

Most of the studies reviewed here involved sampling at the plot level to the micro watershed level. Results from experiments

at these levels need to be extrapolated to larger scales to assess the effect of changing land use/cover and climate on regional hydrology. The extrapolation requires different methodologies for scaling-up the results obtained at the smaller scales, depending on the nature of the experiments. No studies of this topic have been carried out in the Indian context.

Scope for future research

Owing to the paucity of experimental studies and inter-disciplinary studies to evaluate the impact of LU/LC changes on hydrology, it is of immediate necessity to focus future research on the following topics.

(1) Characterization of the physical and chemical properties of soils is essential. Soil physical characteristics can further be used to represent the soil properties in hydrological modeling. Therefore, it is an urgent need to understand changes in soil physical properties.

(2) Greater attention should be directed toward better understanding of runoff generation mechanisms which can lead to development of a conceptual framework for estimation of floods from the primary catchments under the changing climatic and land use/land cover scenarios.

(3) Use of spatial hydrological models to evaluate impacts needs to be considered to fully understand the impacts of LU/LC changes on regional hydrology.

(4) Studies of paired catchments are needed to evaluate the impacts of land-use and land cover changes on hydrological and resulting socio-economic impacts either at the micro-watershed level or the regional level.

(5) There is need for developing a conceptual framework to extrapolate (scale-up) the results obtained at plot or micro-watersheds to meso-scale.

(6) Finally, it is essential to initiate an inter-disciplinary and participatory exploration of the links between land-use, watershed functions and socio-economics to assess the impact in its totality.

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